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Oceanographic Variability in Shallow-Water Acoustics and the Dual Role of the Sea Bottom

Hassan B. Ali

***Abstract*— Acoustic propagation in shallow water is an area of major concern to the Navy. The difficulties associated with the use of acoustics in the ocean, however, are aggravated in shallow water. Multipath propagation and extensive boundary interactions, especially with the sea bottom, conspire, along with a host of other phenomena, to produce a highly variable and often unpredictable acoustic field. The responsible mechanisms, and hence the acoustic effects, cover a wide range of temporal and spatial scales. The mechanisms are classified as either deterministic or random, although the two types often act in concert. The sea bottom plays a dual role in shallow-water acoustics. Because of extensive interactions with the sound field, the bottom can severely degrade waterborne propagation. On the other hand, the sea bottom (and subbottom) can provide a *seismic* path that not only is relatively stable, but exists even under environmental conditions that preclude an effective waterborne path. Propagation in the bottom is particularly significant at very low frequencies, often being more efficient than high-frequency waterborne propagation. The preceding aspects of shallow-water acoustics—viz., variability and the dual role of the sea bottom—are illustrated using the results of experiments conducted in diverse geographic areas by the Naval Research Laboratory/SSC and by the SACLANT Undersea Research Centre.**

I. Introduction

THE CONTINENTAL land masses of the earth are surrounded largely by shallow water, the precise delineation of the coverage being dependent upon the meaning one assigns to "shallow water." By any reasonable criterion, however, it is obvious that all commercial and military shipping must pass through shallow water when entering or leaving port, or when transiting straits or passages. This high density of marine traffic suggests that a naval confrontation, should it occur, could very well be in shallow water. Consequently, shallow water, and in particular shallow-water acoustics, is an area of major concern to the Navy. Effective exploitation of shallow-water acoustics is, however, frustrated by the inherent and well-known complexity of the acoustic medium. Multipath propagation and extensive boundary interactions, especially with the sea bottom, conspire to produce a highly variable and often unpredictable acoustic field. The spatial and temporal variabilities in the field impose severe constraints on signal processing schemes. In particular, limits are imposed upon signal processing integration times (by fluctuations and loss of temporal coherence), on filter bandwidths (by frequency spreading/temporal decorrelations), on maximum array gains (by loss of spatial coherence and/or anisotropy of ambient noise), and on bearing accuracy of the sound source (by spatial coherence loss/angular spread). It is difficult, if not impossible, to completely overcome these signal degradations, especially with conventional signal processing schemes, since they are concomitant attributes of sound propagation in the ocean environment. Not surprisingly, the instability of the acoustic field is a central issue in shallow-water acoustics; it manifests itself not only in the "signal" per se, but also in the ambient noise behavior, reverberation, and bottom propagation. Conversely, the preceding are among the major contributors to the variability of the acoustic field.

The sea bottom is of paramount interest in shallow-water acoustics, particularly at low and very low frequencies. This stems from the fact that the sea bottom serves a dual role in shallow-water acoustic propagation: extensive bottom interactions can severely degrade *waterborne* propagation; on the other hand, the sea bottom (and subbottom) can provide a *seismic* path that not only is relatively stable, but exists even under environmental conditions that preclude an effective waterborne path. Variability, and the role of the sea bottom in sound propagation in shallow water are the central themes of this paper. The primary causes of spatial and temporal variability will be reviewed using, wherever possible, examples from the author's own experience and research. Next, the influence of sediment and subbottom properties on partitioning acoustic propagation between waterborne and bottom paths is demonstrated, using the results of past experiments and current research at the Naval Research Laboratory (NRL/SSC). Finally, an example is given of the effects on acoustic transmission of environmental variability and bottom interaction acting in concert. No attempt is made at complete coverage of all sources of variability. Consequently, some topics, such as the influence of the sea surface, have largely been omitted.

II. Environmental Variability and Acoustic Fluctuations

Overview

The propagation of sound in the ocean is inevitably accompanied by fluctuations in the amplitude and phase of an acoustic signal received at large distances from the source. The fluctuations are manifestations not only of changing patterns of interaction with the bottom and surface, particularly important in shallow-water propagation, but also passages of the wave through time-varying inhomogeneities in the ocean medium. The resulting fluctuations, or scintillations,

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in acoustic intensity are analogous to the twinkling of stars arising from multiple scattering of lightwaves in the irregular layers of the upper atmosphere. The variability in acoustic propagation can be considered to arise from variations in the index of refraction, or sound velocity, of the medium, which, in turn, are induced by a variety of ocean processes covering a wide range of temporal and spatial scales. The scales of variability of significant ocean processes will be summarized, using the results of an earlier review by the author [1].

Spatial and Temporal Scales of Ocean Variability

Table I summarizes the environmental phenomena and their acoustic effects. Depending on the temporal and spatial scales involved, the mechanisms can be considered either deterministic or random [1]. The general circulation of the ocean ("ocean climate") and its associated current systems (Gulf Stream, Kuroshio, etc.) are characterized by horizontal scales of variability limited only by the size of the basin, vertical scales of a few hundred meters, and temporal scales from a few days to seasonal. These are deterministic structures. The intermediate scales of variability, including ocean motions such as fronts and eddies, can also be considered to be deterministic perturbations from the mean structure. The associated scales of variabilities are of the order of 100 to 1000 km in the horizontal, to ocean depth in the vertical, and days to months in time. Smaller scale phenomena comprise internal waves, fine-structure, and microstructure. With certain exceptions, described below, these phenomena are considered random.

Fine- and microstructure variability involve scales from several meters to hundreds of meters in the horizontal and 1 cm to about 10 m in the vertical. It is of the order of milliseconds in time. Such variability would be expected to affect sound propagation in the frequency range from approximately 1 to tens of kHz.

Internal waves are characterized by scales from 100 m to 10 km or more in the horizontal, 1 to 100 m in the vertical, and from about 10 min to 1 day in time. Because they owe their existence to the restoring forces due to the density gradient and the Coriolis force, the frequency spectra of internal waves are bounded by the inertial frequency at the low end and by the buoyancy frequency (Brunt–Väisälä) at the high end. Internal wave-induced variability has been found to be a very significant source of sound scattering and has received considerable attention in recent years [2]–[4]. In essence, this increased activity arises from two complementary facts. On the one hand the spatial scales of internal waves match the acoustic wavelength over a broad frequency range, and thereby affect the acoustic field; on the other hand the internal wave is one of the few phenomena for which a reasonably effective statistical model (Garrett–Munk) is available. Using an extensive set of existing deep-water measurements of fluctuation spectra associated with oceanic velocity and temperature fields, Garrett and Munk (1972) developed an empirical model of the internal wave spectrum based on linear internal wave theory. With the exception of inertial waves and internal tides the Garrett–Munk (GM) model is considered to represent a universal deep-water internal wave spectrum. Not surprisingly, much of the experimental and theoretical activity in internal waves in recent years has been related to the GM model (for additional information and extensive references see Gregg and Briscoe (1979); Levine (1983); and Olbers (1983)). In spite of the widespread success of the GM model, the reason for the existence of a universal spectrum is apparently still unclear. The mere existence of a universal spectrum—i.e., the fact that wherever one is in the deep ocean, the internal wave scales and amplitudes can be scaled by the local buoyancy and inertial frequency—suggests that some sort of saturation limit has been reached. This, in turn, requires a relatively uniform energy source and effective non-linear coupling to redistribute the energy over the spectrum, regardless of where it is put in. The mechanism for the preceding is yet to be clarified (Dugan, 1979; Garrett and Munk, 1979). In a recent article by Allen and Joseph (1989) an attempt is made to obtain a theoretical understanding of the GM model, based on first principles. In particular, the methods of statistical mechanics are applied to weakly interacting internal waves by using the Lagrangian description of fluid dynamics rather than the more commonly used Eulerian approach. Based on first principles, the authors derive the GM energy spectrum and show that it is not a fundamental property of the system (as is, for example, a Maxwellian distribution for a gas), but rather is partly a consequence of the process used to measure internal waves.

In the upper ocean and in shallow water the GM model turns out to be inappropriate, partly due to the strong influence of the atmosphere (wind stress) and the fact that the waveguide properties of these environments are considerably different from those of the deep ocean. In shallow water, the internal wave appears to have a deterministic nature, characterized by propagation of a solitary wave, or soliton (Zhou *et al.*, 1991). The soliton is a wave-packet-like propagating disturbance that retains its shape because of the opposing effects of dispersion (tending to spread the packet) and nonlinear effects (tending to steepen and confine the packet). Large-amplitude internal solitons have been observed in numerous coastal regions of the world and in lakes (see Zhou, 1991), although, as pointed out by Ostrovsky (1989), not all observed solitary perturbations are solitons. In coastal waters, deterministic groups of internal waves with well-define wavelengths, i.e., solitons, are usually observed in summer when they are trapped in a strong and shallow seasonal thermocline. Solitons have been found to be highly correlated with the tides and to propagate shoreward. They seem to be generated by the interaction of a tidally driven flow with sills, continential shelf edges, or other major variations in underwater topography (Zhou, 1991). As noted in a subsequent section, the characteristics of solitons have been satisfactorily described by theory.

An Example of Measured Temporal Variability

Fig. 1 provides an example of the variation of sound speed with depth over a period of 25 hours. The result is from an experiment conducted by SACLANTCEN in shallow water (80 m) of the Mediterranean Sea during summer conditions (Ali *et al.* [14]). Fig. 1(a) plots in the usual manner the

TABLE I
ENVIRONMENTAL PHENOMENA AND THEIR ACOUSTIC EFFECTS

Phenomenon	Spatial Scales		Temporal Scales	Comments	Acoustic Parameter Affected
	Horizontal	Vertical			
Ocean Climate (General Circulation)	Up to entire Ocean Basin	A few 100 m	Days to Seasonal	Greatest variability occurs in surface layers	•Acoustic amplitude •Acoustic phase •Propagation path
Mesoscale (Ocean Weather)	50 to 500 km	Up to Ocean depth	Days to months	•Includes eddies and fronts •Deterministic perturbations from mean structure	•Propagation path •Acoustic intensity •Signal travel time •Signal Shape
Tidal	Variable	Wave height can exceed 10 m. but subsurface effects may extend to greater distances	Diurnal and semi-diurnal	Includes the following mechanisms: •Tidal changes in water depth •Tidal streaming •Depth dependence of tidal streaming •Tidal changes in water structure (including the introduction of tidal-period internal waves)	•Acoustic amplitude fluctuations are generally noise-like •Acoustic phase fluctuations are simply correlated with tidal variations •Acoustic effects are greater in shallow water
Internal Waves	100 m to 10 km (can be much larger)	1 to 100 m	10 min to approx. 1 day	DEEP WATER: •Broadband Garrett–Munk frequency spectrum bounded by inertial frequency at low end and Brunt–Vaisala frequency at high end •Stochastic perturbation from mean structure SHALLOW WATER • Narrowband spectra characterized by intermittent, deterministic (soliton) propagation. •Tides and bathymetric features significant in soliton generation. •Observed in summer for strong, shallow thermocline.	•Acoustic amplitude •Acoustic phase •Significant effect on nearly horizontal ray paths •Amplitude, spatial and temporal coherences affected by solitons
Fine Structure	10's to 100's of meters	1 to 10 m	Milliseconds	•Characterized by step-like structure in temperature, density, salinity, current	•Propagation paths •Phase fluctuations •Amplitude fluctuations
Microstructure	Many meters	Centimeters	Milliseconds	•Generation mechanism similar to that for fine structure •Includes turbulence	•Scattering of high frequency (5 kHz and higher) waves •Fluctuations in acoustic amplitude and phase

sound speed profiles over approximately hour intervals. In Fig. 1(b) the same profiles are displayed side by side to clearly demonstrate the nature of the variation, while Fig. 1(c) is shown to emphasize the sound speed fine-structure. From the surface down to about 20 m the region appears to be essentially isovelocity with sound speed of approximately 1538 m/s. The depth from approximately 25 to 35 m comprises the steepest portion of the thermocline. Fluctuations in sound speed are quite evident, particularly at a depth of about 25 m within the thermocline. The plot clearly indicates an oscillation in the thickness of the mixed layer (surface duct). Further, "kinks," typical features in the curve, appear to migrate vertically with time—a motion often suggesting the presence of internal waves (Gregg [15]). Of particular note is the fine-structure evident in the expanded portion of the profile (Fig. 1(c)). Generally, the fine-structure in this example was characterized

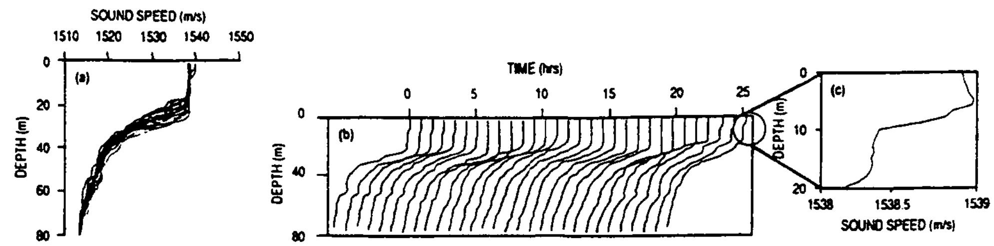

Fig. 1. Temporal variation of sound speed over approximately 25 hours.

by vertical dimensions of the order of a few centimeters to one or two meters. As already noted, this fine-structure tends to scatter high frequency sound.

The frequency content of the oscillations in the sound speed profile is of particular interest because it provides clues to the mechanisms responsible for the fluctuations. An examination of the frequency spectra [14] reveals that the dominant fluctuations occur in the frequency range from 0.06 to 0.08 cycle/h, which coincide with a range of periods of 17 to 12 hours, respectively. Within this broad response are included both the semi-diurnal and inertial periods (approximately 17 hours for this area). A longer time series than was used here would probably have enabled the spectral separation of the two responses. From the results obtained at other depths it does appear, however, that the relative significance of the semi-diurnal tidal and inertial effects depends on depth. Apparently there are fluctuations of inertial period in the surface layers, and, as the depth increases, the dominant fluctuations are semi-diurnal. Inertial oscillations may occur in connection with a sudden change of the wind speed (i.e., a wind gust of short duration) and rapid changes in barometric pressure [16]. The whole Mediterranean is dominated by meteorological forcing; therefore, it is likely that inertial oscillations are present in the study area. A comparison of these spectra with spectra from the acoustic transmission loss reveals a good correlation between the two. Reference [14] provides additional details.

The Effect of Temperature Fluctuations in the Water Column on Sediment Properties

It is clear that fluctuations in the water column parameters affect not only the propagation of sound in the water column, but also the manner in which the sound interacts with the sea bottom. Less obvious is the fact that these fluctuations can also modify the properties of the sea bottom. Yet this is precisely the conclusion of recent investigations by Rajan and Frisk [17], [18]. Using data obtained at different seasons but at the same location in the Gulf of Mexico, the authors investigated the seasonal variation of the sediment compressional wave-speed profile due to temperature variability in the water column. It was hypothesized that heat flow from the bottom of the water column into the sediment affects the sediment pore water temperature, thereby influencing the temperature structure, and thus the compressional wave speed, in the sediments. Since this heat flux varies with season, the effect on sediment compressional wave speed should also change seasonally. In the shallower depths (<30 m) of the Gulf of Mexico, seasonal fluctuations in the ocean bottom temperature as great as 15°C have been observed.

The authors investigated the heat flux across the water/sediment interface and, using a Biot model for the sediments, assessed its effects on the compressional wave speed in the sediment layers. They showed that the compressional wave speed varies approximately linearly with pore water temperature, an effect which is, to first order, independent of both the porosity and sediment type. Applying a perturbative inversion technique to the two data sets from the Gulf of Mexico, the effect of variations in water column temperature on sediment compressional speed was demonstrated. The experimental results indicate that the influence of the water column is felt to substantially greater depths in the sediment than predicted by the theory. As a final point, the authors note that the temperature-induced variations in the bottom compressional speeds can have important effects in the prediction of the pressure field in the water column (especially at higher frequencies), and also on source localization schemes like matched-field processing.

Theoretical Approaches to Variability

Theoretical approaches to the propagation of sound in a realistic ocean environment are still evolving. Models of the underwater acoustic medium can be categorized as macroscopic or microscopic. Macroscopic models characterize the medium by its mean velocity (sound speed profile) and are useful in providing estimates of range, depth, and coverage for sonar and communications. Many of the numerical models of propagation currently in use fall into this category. Well-known ones include the parabolic equation (PE) method, fast field programs (FFP), the normal mode method, finite element methods, finite difference approaches, etc. However, these models do not describe nondeterministic deviations from the mean; that is, they cannot handle random (stochastic) behavior of the propagation.

Attempts to understand the nondeterministic component of acoustic intensity fluctuations have been centered around the theory of propagation through a random medium. The only medium descriptor needed in such a theory is the correlation function of the fluctuations (index of refraction) or its equivalent (structure function, spectrum). Because the pertinent stochastic wave equation cannot be solved deterministically, solutions are obtained in terms of statistical moments of the acoustic pressure, such as the expected value (ensemble average), various correlation functions, and higher order moments.

The fourth moment is of particular interest since this gives the intensity fluctuations.

Earlier theories of intensity fluctuations were based on either the Born approximation or the Rytov Method of Small Perturbations. These approaches are valid for the weak or single scattering cases, which are adequate for high frequencies and/or short ranges. In particular, the Born approximation is valid only for small fluctuations in both the intensity and the phases; the Rytov method is valid for small intensity fluctuations, but has less stringent requirements in phase.

Much of the new work in extending the range of validity to large intensity fluctuations arising from multiple scattering is based on the nondeterminstic version of the PE method. The PE method is a simplification of the wave equation for the case of scattering that is mostly in the forward direction. The two main methods of solving the PE are the Feynman path integral (used by Flatte, *et al.* [3]) and the moment-equation (used by Uscinski, *et al.* [4]). Both methods have had some recent success in attributing measured intensity fluctuations to the action of internal waves [3], [4] in deep water. As alluded to earlier, this has been possible because of the availability of the required statistical description of the stochastic medium, viz, the GM empirical model.

As already noted, the GM model is inappropriate for the explanation of internal wave propagation in shallow water. The soliton propagation observed in shallow water is explained by the Joseph generalization of the Kortweg-deVries (KdV) equation, which describes weakly nonlinear and weakly dispersive one-dimensional waves (Joseph, 1977; Ostrovsky, 1989). The solutions obtained yield a "sech^2" form for the soliton wave amplitude. Not surprisingly, the concept of solitons is not restricted to shallow water acoustics, nor did it originate in this field. To cite a few examples: solitons in the form of localized wave packets appear as solutions to the nonlinear Schrödinger equation; some physicists have suggested that an elementary particle is actually a soliton; nonlinear effects are known to cause optical solitons in glass fibers; etc. (Ablowitz, 1991; Segur, 1991; Knight, 1989).

III. The Effects of the Sea Bottom

Relevant Aspects of Shallow-Water Acoustics

The distinction between shallow and deep water is imprecise, and often depends on the particular application. In one common definition, shallow water comprises those areas of the ocean overlying the continental shelves. This is roughly equivalent to defining as shallow those areas having depths less than a 100 fathoms, or about 200 m. Another definition requires the ratio of water depth to acoustic wavelength to be "relatively small"—sometimes meaning less than 10. For acoustical applications these definitions are clearly unsatisfactory, since they exclude some obvious and important conditions. For example, even in coastal waters "high frequency" sound displays propagation characteristics typical of those for deep water. Similarly, at sufficiently "low frequencies" propagation in normally deep water is consistent with shallow water behavior.

A more quantitative discriminant is based on the demarcation between ray treatment and normal mode treatment of acoustic propagation (Weston, 1963 [23]). In particular, in terms of range (r), water depth (H), and acoustic wavelength (λ), the expression $r = H^2/\lambda$ defines a critical range below which ray treatment is more useful and above which modal treatment is preferable. Since, loosely speaking, the ray/mode split tends to divide deep from shallow water, the above expression also defines a depth ($H = \sqrt{\lambda r}$) below which the water can be considered acoustically shallow. Although "better" than the previous definitions, this one, too, is not perfect since it is tantamount to equating shallow water propagation with mode propagation, an identification which is not always valid. Lacking an unequivocal quantitative definition of shallow water, a qualitative understanding will have to suffice. Since proximity of the surface and bottom boundaries is the essential factor determining the behavior of shallow water acoustics, "shallow-water propagation" will be taken to imply significant interaction of the acoustic field with the boundaries.

With the preceding in mind, a number of the well-known characteristics of shallow-water acoustics become intuitively obvious. The proximity of the bottom rules out the long-range propagation paths, such as convergence zone and bottom bounce, which are made feasible in deep water by the positive sound speed gradient at greater depths. In the first place, the limited water depth generally precludes deep refracted waterborne paths. Moreover, repeated interactions with the bottom result in significant loss due to attenuation, thereby severely limiting long-range propagation. The effect of the sound-speed profile is thus generally less important in shallow water than in deep water; it does, nevertheless, determine the *likelihood* of bottom interaction. A negative gradient in sound-speed profile, typical of summer conditions, generally leads to a greater likelihood of bottom interaction, and thus to greater bottom losses. As a result, for otherwise identical propagation paths transmission losses in shallow water are significantly greater in summer than they are in winter (Akal [24]).

Waveguide-Like Behavior of the Shallow-Water Duct

The most salient feature of shallow water is undoubtedly its behavior as a waveguide, albeit a partial or imperfect one, for the propagation of sound (Pekeris [25]). Thus for a wide range of angles and frequencies, acoustic energy is "trapped" and propagates within the duct as discrete, frequency-dependent modes. Below a certain cutoff frequency, which is dependent upon water depth and relative sound speeds in the water and sea bottom, effective propagation ceases to exist within the waveguide formed by the sea surface and bottom boundaries. Instead, energy is transferred from the trapped discrete modes into the so-called "continuous spectrum" of energy in the bottom.

From the viewpoint of ray acoustics, the transference from discrete to continuous modes occurs at the critical angle, $\Theta_c = \cos^{-1}(c_w/c_b)$; c_w is the sound speed in water, c_b is the speed of the appropriate body wave (either shear or compressional) in the bottom. For grazing angles (relative to the horizontal) less than critical, much of the incident energy (all, if the bottom is lossless) is reflected, resulting in the propagation of discrete modes. For grazing angles greater than the critical angle, significant transmission into the bottom occurs, giving rise to continuous modes which, because they decay more rapidly then $1/\sqrt{r}$, are largely confined to the near wave field. In realistic environments, particularly soft seabeds, the critical angle does not serve as a sharp demarcation, and some energy "leakage" into the bottom occurs even at low grazing angles. In soft seabeds, for which the value of the sound speed in water (c_w) lies between the compressional speed (c_p) and the shear sound speed (c_s) (i.e., $c_p > c_w \gg c_s$), the critical angle for shear is absent, which explains why leakage occurs even at low grazing angles. The leakage means that the waterborne modes are no longer strictly discrete, since as they propagate they decay exponentially with range. These leaky modes (also called quasi-discrete, pseudo-, or virtual modes) dominate the propagation for low grazing angles. For hard seabeds ($c_p > c_s > c_w$) energy loss into the bottom is less significant at low grazing angles, since both shear and compressional critical angles exist.

A fundamental feature of shallow-water (waveguide) acoustic propagation is *geometric dispersion*: the speed of propagation depends on frequency. Typical dispersion curves (group velocity versus frequency) show that the group velocity varies from the speed of the ground wave at the low cutoff frequency to the waterborne speed at the high frequencies, with a minimum speed at an intermediate frequency [25]. As a result, a broadband impulsive signal (e.g., an explosion) in shallow water will generally lead to the following type of disturbance at a distance from the explosive source. The first arrival will be a low-frequency wave train representing energy traveling primarily through the higher speed seabed. This "ground wave" will be followed by the higher frequency waterborne direct-path arrival. The high-frequency waterborne wave is followed by a region in which waterborne and late-arriving ground waves interfere and eventually die away. From the characteristics of these various arrivals, particularly the ground waves, information on the geoacoustic properties of bottom and subbottom strata may be inferred, even for a complex environment. This is demonstrated in the following section.

IV. Relative Contributions of Waterborne and Sediment Paths

A Quantitative Measure of Spectral Energy Partitioning

Partitioning of acoustic energy between waterborne and bottom paths (seafloor and subseafloor) has been a subject of some interest for several decades, even pre-dating the pioneering work of Pekeris. In recent years, however, partitioning has gained substantial attention because of the increased interest in low-frequency acoustic propagation. At low frequencies, particularly very low frequencies (VLF, {<}20 Hz), the relatively small sediment attenuation allows significant penetration of acoustic energy into the seafloor, thereby necessitating inclusion of the effects of the seafloor on the propagation of the energy. To effectively assess the various factors influencing energy partitioning requires, as a minimum, a quantitative measure of the partitioning itself. A complete experimental quantification of the partitioning of physical energy at the seafloor into the various modes of propagation requires an array of receivers that defines the full seismo-acoustic wavefield on both sides of the interface. At best, this is highly impractical. An extremely useful and realistic, albeit more restrictive, quantitative measure has recently been used by NRL to analyze the results of a VLF experiment (Ali [26]). A discussion of this measure and other relevant results from the VLF experiment forms the remainder of this section.

First, the relevant aspects of the VLF experiment will be briefly summarized; further details are provided in [26]. The experiment was conducted in 1987 off the coast of Oregon in water ranging in depth from approximately 180 m to 2740 m. A 16-element vertical hydrophone string was deployed in water depths of 183 m and 373 m. In addition, several ocean bottom seismometers (OBS) were deployed at various locations on the seafloor. Using explosives, air guns, and a *cw* sound source (fundamental frequency, 15 Hz), several upslope and cross-slope lines were completed. In this paper we present the response of the top hydrophone, located 293 m below the water surface and 80 m above the bottom, to shots dropped along a 120-km long line beginning in shallow water (190 m), passing the hydrophone string, and terminating in deeper water (2740 m). The shots consisted of 55-pound TNT charges and were detonated at depths ranging from approximately 60 to 90 m.

To clearly establish the basis for the measure of partitioning used in this paper, a typical response to an underwater explosion ("shot") is discussed. Fig. 2 presents the measured response of the water column hydrophone to a 10 km-distant shot. The length of the record shown here is approximately 6 s. Characteristic features of the response are labelled. The low-frequency arrival preceding the waterborne wave—i.e., the ground wave—represents energy traveling at a speed greater than that of the waterborne wave; hence, this is energy propagating in the bottom for a large part of its travel path. The frequencies contained in the ground wave are generally very low (here predominantly less than 10 Hz). The higher frequency components of the signal have been attenuated during deep penetration into the bottom layers. Generally, the high-speed ground waves will be dominated by compressional body waves and shear body waves converted to and from compressional body waves at the seafloor or subbottom layers.

As noted earlier, analysis of the ground wave can provide information on the geoacoustic properties of the bottom and subbottom strata. In most of the shot records the ground wave appears to consist of several (two or three) packets of energy commonly referred to as distinct arrivals or seismic phases. This is often indicative of several bottom strata of different geoacoustic properties. However, a simple correspondence of phases with subbottom layers is not necessarily correct since multipath propagation will typically generate more arrivals than there are layers. Based on vertical component geophone data obtained on a nearby OBS, we believe the early part of the ground wave arrival in Fig. 2 is energy returning from below acoustic basement. Acoustic basement in this area consists of a lithified sediment (clastic sedimentary rocks,

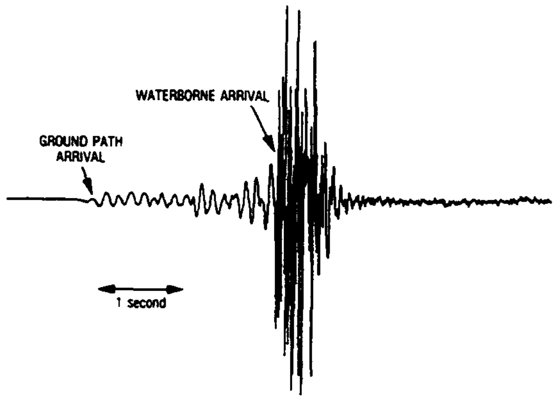

Fig. 2. Hydrophone response to a 10-km distant explosion (55-pound TNT), showing ground wave and water path arrivals.

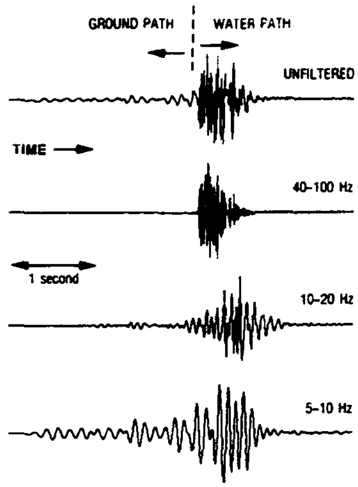

Fig. 3. Frequency selectivity of the propagation paths.

consisting of sandstones, claystones, and siltstones) 1500 m below the seafloor. The later higher amplitude ground wave arrivals probably represent energy returning from depths shallower than this. The arrival of the high-frequency waterborne acoustic wave is followed by a region in which waterborne and late-arriving ground waves interfere and eventually die away. These late-arriving ground waves can be attributed to multipath propagation in the slow-speed shallow sediments.

Based on the preceding, a reasonable first-order measure of deeply penetrating paths is provided by the total spectral energy in the time series comprising the high-speed, low-frequency ground waves preceding the waterborne arrivals. By including all of these multiple phases under the category of ground path contribution, a parameterization is produced which is more stable and less dependent on the details of the propagation path. The spectral energy in the time series comprised of subsequent arrivals, beginning with the acoustic water wave, represents energy propagating predominantly in the water column and upper sediment layers of the sea bottom. Hence, the ratio of the two spectral energy terms is a useful parameter to assess the relative contributions of the two paths: deeply penetrating bottom/subbottom paths versus waterborne and shallow-sediment paths.

Frequency Partitioning of the Propagation Paths

To examine the role of frequency selectivity in determining the relative importance of the ground and water paths, the response in Fig. 2 was bandpass filtered into three different frequency bands. The original (unfiltered) data and the filtered responses are shown in Fig. 3. The sediment refraction (ground path) and water path are readily distinguishable on the basis of frequency content. In particular, the increase in relative importance of the ground wave with lower frequencies is quite evident. High-frequency propagation is significantly attenuated in the ground path, but is clearly dominant in the water path. Above 40 Hz, for example, the ground wave is not even discernible in this particular signal.

Range-Dependent Effects on the Relative Contributions of the PropagationPaths

In a realistic ocean environment it is expected, *a priori*, that the relative energy between the water and ground paths will be influenced by changing distance from the sound source. In addition to obvious geometrical spreading of the acoustic waves, changes in water depth result in modifications of the modal structure of the water column acoustic energy and therefore in the overall amplitude of water path phases. Varying sediment properties and bottom roughness influence the amplitude of the bottom interacting portion of the water path arrival. The amplitude of the ground path as a function of range is governed predominantly by the subbottom compressional (and to a lesser extent shear) velocity structure. The depths and magnitudes of major discontinuities between sedimentary layers and the velocity gradients within those layers exert strong controls on the focusing of energy emerging from the seafloor at different ranges. Scattering of energy by subbottom seismic velocity heterogeneities will result in redistribution of the emerging energy to different ranges and energy losses associated with scattering of energy out of the sagittal plane.

Examination of the range-dependence of the data reveals that the ground waves becomes indiscernible above background noise at ranges exceeding approximately 20 km on either side of the hydrophone—that is, independent of whether the source was in shallow water or deep water. The waterborne arrival, on the other hand, was clearly visible even at the maximum source distance (approximately 100 km). Fig. 4 shows the ratio of spectral energy in the ground wave to energy in the waterborne path as a function of range, in several frequency bands. As expected, the lower frequency band contains more ground wave energy. Relative ground wave energy drops off both with increasing frequency and, in this case, with range. As a result of the test geometry, the greater ranges correspond to deeper water and areas of increasing bottom slope. The peak occurring in shallow water, at approximately 7 km from the source (−7 km), may be due to energy returns from acoustic basement. This is strongly suggested by the record of seismograms at several ranges (record section) obtained from a nearby vertical geophone. The result at this range is discussed in more detail subsequently (in connection with Fig. 5). The peak at +7 km may be associated with an obvious "abrupt" change in bathymetry at that location [26].

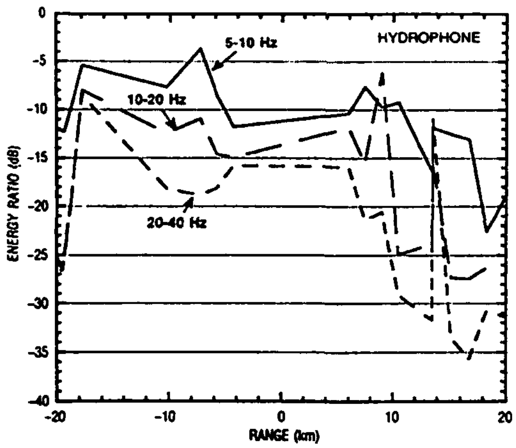

Fig. 4. Ratio of energy in the ground wave to energy in the waterborne path as a function of range and frequency.

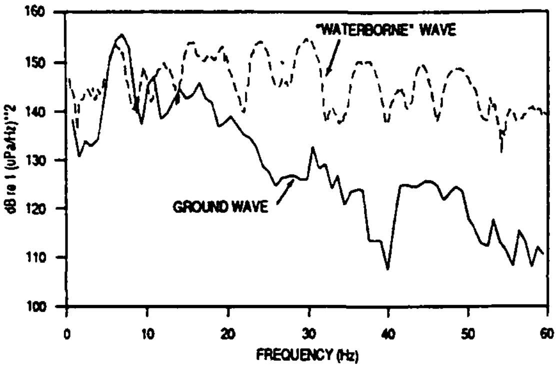

Fig. 5. Spectral energy partitioning between ground and waterborne paths.

On a nearby vertical seismometer sensor, which is more sensitive to deeply penetrating compressional energy because of its vertical directivity, ground waves can be observed to at least 60 km. It is believed that scattering of ground wave energy from subbottom heterogeneities plays a major role in the ground wave energy losses in this environment. Based on sparker profiles performed during the experiment, and on published, interpreted seismic profiles [27], [28], it is clear that the Oregon continental margin is characterized by a complicated bottom and subbottom structure involving faulted and folded sedimentary strata. A similar experiment was conducted in 1985 in the more "benign" environment (passive margin) off Cape Fear, NC. In that experiment, the ground wave arrivals from similar shots were very clear at distances of at least 60 km and were significantly larger than observed in this experiment [29]. The character of the ground waves was also different in the two areas: the signals were more impulsive in the East Coast data while they were more distributed in time with longer wave trains in the Oregon experiment. This observation is consistent with an increased scattering contribution in the Oregon data set that would tend to degrade long range propagation of the ground wave.

To assess the effects of water depth and range on the relative contributions of waterborne and ground paths, a comparison was made of the corresponding energy spectra at several source-receiver distances. Detailed observations are provided in [26], but some general results can be given here. As expected, with the source in deep water relatively good waterborne propagation occurred over a broad frequency range. With the source in shallow water, however, waterborne propagation was degraded, while the ground path was enhanced. At the lower frequencies, much of the waterborne loss in the shallow-water region was likely due to conversion into ground wave energy. While the loss in waterborne energy at the higher frequencies is also likely to be caused by conversion into ground waves, scattering and anelastic attenuation within the seafloor prevent this energy from reemerging as an observed ground wave.

A general observation, independent of range, was the relatively high levels of ground wave energy at the lower frequencies. As noted earlier, the ground wave response at −7 km is conspicuous. This is shown in more detail in Fig. 5, which compares the spectral energies in the ground and waterborne paths. Here, the source was located 7 km from the receiver, in water 395 m deep. It is clear from this figure that at certain VLF frequencies the ground wave component exceeds the waterborne one. Stated differently, in some instances the ground path is even more efficient than the high-frequency waterborne path. In fact, the efficiency of the ground path is somewhat understated by these figures since, as noted earlier, what has been called "waterborne" propagation here includes shallow-sediment ground paths along with the true waterborne ones.

V. An Example of the Combined Effects of Oceanic Fronts and Bottom Interaction

The effects of environmental variability on shallow-water acoustics, and the special role of the sea bottom have been the central issues of this paper. This final section is concerned with a rather interesting situation in which these two factors act in concert to determine the characteristics of the propagation. In particular, the effect of the polar oceanic front on shallow-water acoustic propagation is briefly discussed using the results of a SACLANTCEN experiment conducted in the North Atlantic [30].

Geometry and Environmental Characteristics of the Test Site

The experimental configuration for the North Atlantic test is shown in Fig. 6. The two tracks, A–B and D–C, represent the propagation paths for measurements conducted one year apart. For the configuration shown, broadband sources (explosives) were dropped at hourly intervals. The receivers were vertical arrays of hydrophones. Simultaneous samplings of the pertinent oceanographic parameters (sound speed, temperature, salinity, and density) were taken at both the source and receiver locations.

The North Atlantic test site is a very complex geological, oceanographic, and biological province and has been the object of many investigations [31]. The test site is located in an area affected by a large-scale permanent front resulting from the convergence of two water masses. In particular, at this location, cold, less saline Arctic water meets warmer

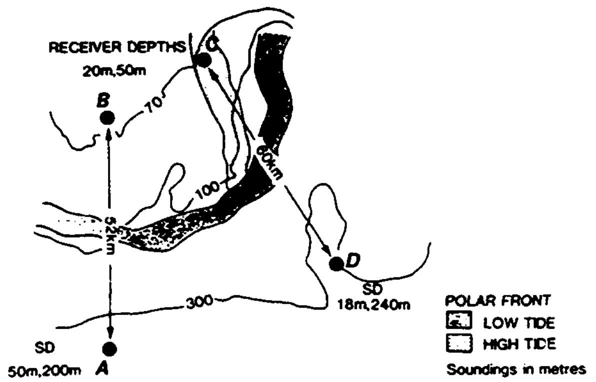

Fig. 6. Geometry of the North Atlantic measurement.

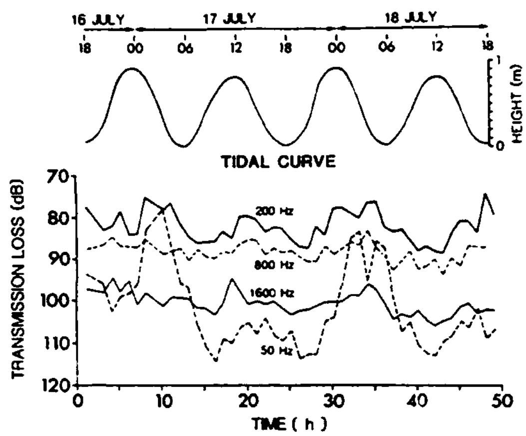

Fig. 7. Temporal variation of transmission losses and predicted tidal curve at site C.

Atlantic water to form the polar oceanic front. The substantial differences in salinity and temperature of the two water-types (35 parts per thousand (ppt)) and 6–7°C for the Atlantic versus 34.6 ppt and about 0°C for the Arctic) cause the polar front to be characterized by steep gradients in these parameters, with significant implications for sound propagation. An added complication arises from the changing position of the front, which oscillates with semi-diurnal tidal periodicity.

The environmental conditions along the two paths shown in the figure were somewhat different. Although both tracks A–B and D–C cross the polar front, in water changing from deep to shallow, track A–B is over a generally hard bottom (sand), while track D–C is over a generally soft bottom (sand, silt, clay). From the point of view of temporal variability, however, a more fundamental difference between the two receiver locations arises from their relative proximity to the polar front. In particular, station C is directly affected by movements of the front, the water above 20 m changing from polar to Atlantic with an approximately 12-hour periodicity, while the waters below 20 m remain of the polar type. In comparison, station B remains in virtually isothermal polar water, north of the front, as shown schematically in Fig. 6.

In effect, the polar front serves as a demarcation line between two different propagation areas. To the north of the front, in isothermal water, an important part of the propagation will be in shallow water under upward-refracting conditions, resulting in small total transmission losses as a result of less bottom interaction. On the other hand, in waters affected by the front, propagation will be under strong downward-refracting conditions, as a result of the steep gradients, and thereby subject to higher losses, particularly at low frequencies. As noted, measurement site B was always in isothermal water, whereas C was periodically subject to the effects of the front. From this, one would expect the transmission losses measured at site B to be both lower in magnitude and subject to less temporal fluctuation than those at site C. Though generally valid, this conclusion is nevertheless based on an oversimplification of the propagation conditions. In particular, the propagation depends not only on the front, but also on frequency, source and receiver depths, bottom conditions (which are different for the two tracks), and possibly other features, such as currents and inertial oscillations.

Selected Results

Fig. 7 provides a typical example of the fluctuations in measured transmission loss at site C for several frequencies, along with the predicted tidal curve for the area. It is clear that the fluctuations in transmission loss correlate well with tidal periodicity, particularly for the lower frequencies. This is consistent with the assumption that the lower frequencies are more affected by the tidally induced change in downward-refracting conditions. Both diurnal and semi-diurnal periodicities are evident, the former seemingly the more significant. Further, there is a correspondence, albeit inexact, between high tide and high transmission loss, consistent with the fact that the front reaches site C during periods of high tide. Although the curves shown are for a particular source/receiver combination (240 m/50 m), the observed trends are fairly representative of all data obtained at this site.

It is instructive to compare the environmental variability at the two positions B and C. An example of the fluctuations in temperature is shown in Fig. 8. It is noted that the corresponding fluctuations in sound speed, not shown here, are very similar, indicating that temperature is the controlling factor in sound speed variations. Several features are immediately evident from the figure. First, it is clear that the amplitudes at C are greater than those at B and, in addition, show a definite dependence on depth. Further, although both data sets reveal tidal effects, they are more conspicuous at position C, particularly at a depth of 18 m. This behavior no doubt reflects the position of the stations with respect to the polar front, station C being directly affected by the movements of the front, while station B is constantly in isothermal waters, as discussed earlier. The significant differences in results between the two locations suggest that tidally advected changes in water masses, as at C, are more important than the indirect tidal effects (changes in water depth, currents, etc.) that are evident at B. The greater energy measured at

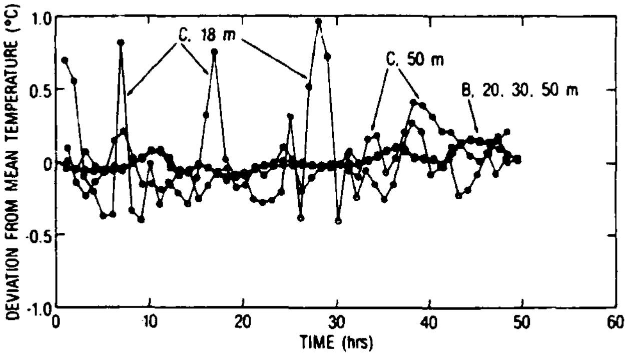

Fig. 8. Normalized temperature fluctuations at the two sites.

18 m (for site C) seems to confirm this conclusion, since the transition zone between the Atlantic and polar waters occurs at this depth. Frequency spectra of the tra .smission loss, not shown here [30], lend further support to the above findings.

VI. Summary and Conclusions

The most pervasive characteristic of the ocean as an acoustic medium is its complex, highly variable nature. A propagating acoustic signal is affected by a host of phenomena, including the sea-surface and bottom, volume inhomogeneities, internal waves and tides, and nonstationary water masses. The responsible mechanisms, and hence the acoustic effects, cover a wide range of temporal and spatial scales and, in general, can be understood only in terms of deterministic and random forces acting in concert. These effects cause fluctuations in the amplitude and phase of an acoustic signal and an accompanying loss in its coherence properties. These degradations, in turn, impose severe constraints on signal processing schemes. The problems imposed by the ocean medium are amplified in shallow water. Multipath propagation and interaction with the boundaries, especially the sea bottom, aggravate an already complex situation, making shallow-water acoustics far more intractable than its counterpart in deep water.

The sea bottom serves a dual role in shallow-water acoustics. While it does play a significant part in degrading a waterborne signal, it also provides an additional, seismic, path for the propagation of sound—particularly at VLF frequencies. Indeed, in some circumstances the ground path can be an efficient means of propagation even in the absence of an effective waterborne path. The ground path is particularly significant for a low-frequency sound source in shallow water. The analysis of the ground path contribution, based on the spectral energy content of the broadband time series, can lend considerable insight into both the propagation characteristics and the geoacoustics of the bottom. In particular, from the character of the early-arriving ground waves (preceding the waterborne arrival) one can infer geoacoustic properties of the bottom and subbottom strata. Further, a comparison of the relevant energies allows an assessment of the relative contributions of deeply penetrating bottom/subbottom paths and waterborne/shallow-sediment paths.

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